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***Abstract*—In order to retain the system stability, the wind power plants are required to provide ancillary services. One of those services is reserve power. Here in this study, we focus on the real-time reserves which can be traded in the balancing markets and are currently used for compensation under mandatory downregulation stated by the transmission system operators (TSOs). The PossPOW project (Possible Power of down-regulated Offshore Wind power plants) developed a real-time power curve of available power for offshore wind farms for use during down-regulation. The follow-up Concert project(control and uncertainties in real-time power curves of offshore wind power plants) aims to quantify and finally reduce the uncertainty in reserve power, bringing the PossPOW algorithm and the state of the art forecasting methods together. The experiments designed to test the available power estimated by the PossPOW algorithm are used to quantify data based, objective uncertainty of the real-time reserves. The results show that the developed algorithm reduces the bias in the wind farm scale available power up to 6% where the uncertainty is improved by approximately 10% for the secondwise calculations. For 30-sec provision case, due to the characteristics of the experiment, circular block bootstrapping is implemented to increase the number of samples. The PossPOW reserve power is shown to have significantly less mean error and uncertainty compared to the good industry practice applied globally.**

I. Introduction

In order to achieve the European climate and energy goals, the share of renewable energy as a proportion of final consumption has increased to 13% in 2012, and is expected to extend further to 21% in 2020 and 24% in 2030 [26]. The accelerated implementation of renewable energy implies many technical challenges particularly for the electricity system, which needs to adjust to the decentralised and highly variable production. Therefore, the modern offshore wind farms are designed as wind power plants required to contribute to the stability of the grid by offering ancillary services (also called grid services). One of those services is reserve power, which is achieved by down-regulating the wind farm from its maximum available power.

The estimation of the available power, or eventually the reserve capacity, is essential as the balancing responsible parties (BRPs) are compensated for this service in terms of the level of reserves. The Transmission System Operators (TSOs) and the BRPs are required to know the amount of production capacity mainly for two reasons; 1) to be able to estimate what the power output will return to when the curtailment instruction is released, 2) to assess the amount of reserves within certain accuracy. The estimated reserves can either be used to calculate the compensation under mandatory down-regulation or can be traded in the balancing market. Most of the regulations are related to the compensation case. However, the reserves can be traded in the balancing market globally with flexible improvements where needed, and these regulations can be applied to assess the accuracy of the reserves as well. The qualification requirements of the estimated available power and relevant technical and market legislations differ regionally. In conformity with the European Network of Transmission System Operators for Electricity (ENTSO-E) policies [1], TSOs are held responsible within continental Europe for the quality of the reserves. The following section provides a brief summary of the existing regional / national regulations in Europe where the grid contains offshore wind power penetration.

A. Global Regulations and Current Estimation of Available Power

1) Belgium: In Belgium, the majority of the reserves is delivered by the conventional power plants where the BRPs are responsible for balancing their portfolio on a 15-min level [2]. Belgian TSO Elia recently performed a pilot project including several tests conducted in Estinnes onshore wind farm [3]. It was investigated whether the design of the current balancing energy market facilitates the participation of wind farms and several changes were proposed. Although not concrete, the potential criteria to evaluate the estimated available power are specified as;

- Average available power calculation error must be close to zero,
- Most of the real-time available power calculation errors should be within a relatively small band around zero,
- Only a limited amount of real-time available power calculation errors can be outside a wider band around zero.

The final feasibility analysis of the required market changes and the targets for pre-qualification will be determined in close collaboration with all market parties in parallel with the developments on the European level.

2) The UK: By the end of 2014, the UK had the largest offshore wind capacity in Europe accounting for over 55% of all the installations [4]. Therefore, to allow better market participation of the renewable generators and enhance the system security, a Grid Code working group focusing solely on the wind farm scale available power provision was formed by the National Grid. It was concluded that [5] the SCADA available power from the individual turbines will be aggregated to the wind farm level, which will shown to be erroneous later in this study. The corresponding signal is to be fed over the existing SCADA data connections used to provide operational metering. No particular accuracy is specified as long as the data quality is in line with the "Good Industry Practice" which will be described later. Additionally, the refresh rate of the potentially provided available power signal is 5-sec, although the actual reserve check is planned to be performed at 10-min intervals. The modification to the Grid Code was into operation on 1 April 2016 without any retrospective application.

3) Ireland: Both Northern Ireland as a part of the UK and the Republic of Ireland have been operating in the Single Electricity Market for the island since 2007. The Irish TSO EirGrid set the quality standard for the available power signal [6] based on the root mean square error, RMS, defined in Equation 1.

$$RMS = \sqrt{\frac{\sum_{h=1}^{h=p} (AP_h - MG_h)^2}{p}} \quad (1)$$

where AP_h is the available power and MG_h is the actual power output recorded by EirGrid averaged over the interval h within a period p. For the same period, the RMS is normalised using the maximum of the installed or maximum export capacity. The normalised RMS is calculated at 15-minutes intervals and has to be lower than 6% when calculated over a day. The standard in the available power estimation also fails when the estimation exceeds the greater of the installed or maximum export capacity by more than 6% in any quarter hour period.

4) Germany and the Netherlands: In Germany, the estimation of the reserve power during down-regulation is compulsory and data requirements from the BRPs during down-regulation are specified both at wind turbine and wind farm level [7]. At the turbine level; the operational state, produced power, wind speed and direction together with the source of the measurements (e.g. nacelle anemometers from the sites or FINO1 as a reference or farm average, etc.), theoretical possible power calculation (based on the certified power curve for the air density $1.225kg/m^3$), a correction factor for the air density and the cost per kWh are to be delivered. For the wind farm level; the sum of the individual theoretical possible power calculations, wind speed and direction, the limitation in power and the power measured at the point of common coupling (PCC) are to be submitted. For the delivered wind speed data and the theoretical possible power calculations, the nacelle anemometers are encouraged to be used. In case they are not available, the reference FINO1 data are to be considered. The provision of the turbine level available power that is based on the nominal power curve with a resolution of $0.1m/s$ should also include the wake losses at the turbine locations. The required time resolution for the data and the calculations are 15-minutes. The compensation and the reserve capacity claims are based on complex operational state descriptions [8].

The Dutch TSO TenneT in the Netherlands, which operates also in Germany, collects and stores the available power data in 15-minutes intervals. However, the reserved capacity is not compensated, even under mandatory curtailment.

5) Denmark: As a world record holder by getting 39.1% of its electricity consumption from wind in 2014 [4], it is only expected that the most detailed regulations regarding the available or reserve power are implemented in Denmark. Since the system is highly dependent on wind, the downward regulation is ordered rather frequently and the BRPs are compensated for their lost production according to the legislation set by the Danish TSO Energinet.dk [9]. The signals to be provided to settle non-supplied generation are: online active power measured both at the installation and the PCC, and online calculation of available and reserve power. Data is to be submitted as 5-minute time series and transferred to Energinet.dk once a day. In order for the settlement to be valid and the compensation to take place, the calculation of the available power must be verified. The error of the provided calculations are to be within $\pm5\%$ span of the actual production for the wind farms ordered to produce in the range of 20 – 100% of the maximum power. Although the data is submitted in 5-minutes intervals, the error in the available power estimation is checked on 15-minutes average basis. If the deviations are outside of the $\pm5\%$ span, Energinet.dk demands the calculation to be corrected and the model to be verified and approved. For consistent over-estimation cases, Energinet.dk calculates a correction factor to reduce the estimated non-supplied generation. Since an actual measurement of the available power is out of the question, the deviations are calculated for the most recent, entire day of normal operation on a site-specific basis. In the same dataset, if the 15-minutes averaged available power is over-estimated (i.e. $>5\%$ of the actual power) for more than 5% of the time, the correction factor is determined as the largest quarter-hourly deviation. This corresponds to a direct deduction from the compensation which seems to be experienced by the BRPs in Denmark rather commonly [8].

Not only in Denmark but also in other places, the risk of not being able to up-regulate to the approximated value is an important concern regarding the over-estimation. In order to make sure the estimated reserve is actually provided, the common practice is to down-regulate extra which might correspond to substantial reduction in profit at times. For example, Sorknæs et al. [10] demonstrated using Sund & Bælt's turbines in Denmark that, depending on the market structure and online prices, participation in the balancing market by providing downward regulation can increase the profit as significantly as 196%. Furthermore, the power balancing across the borders leads to market based shut-downs or down-regulations in the neighbouring country. For example, TenneT TSO GmbH in Germany paid Danish wind farm owners (or BRPs) to curtail 37 GWh of wind power in November 2015 to avoid cutting German output where for the first 11 months of the year, the total down-regulated wind power in Denmark is recorded as 237 GWh in 2015 [11].

The technical regulation and limitations (e.g. response time, duration, etc.) regarding mainly the primary and secondary frequency control are not considered in detail in this study but if interested a further reading is encouraged [12].

What is seen from the existing European regulations is that adequate and standardised regulations or technical requirements to help understanding the possible power or the amount of reserves for their system reliability is lacking. This research is critical not only for power stability but also for the business case for wind energy.

B. PossPOW Available Power

The modern offshore wind turbines have a supervisory control and data acquisition system (SCADA) signal called available [13] or possible power [14]. Since the available power is the maximum power production capacity of the turbine(s) for that particular wind regime, that SCADA signal would be equal to the active power under nominal operation. "The Good Industry Practice" or the state of art in the wind farm scale available power estimation is to aggregate those turbine level SCADA signals. However during down-regulation, the upstream turbines are tuned to extract less power from the wind, leaving the downstream flow more energetic. Therefore, the sum of the individual SCADA signals is a clear over-estimation of the available power of a down-regulated wind farm simply because the wind speed is higher at the downstream turbine location(s) due to the decrease in wake losses under curtailment. As seen in the previous section, the BRPs and the TSOs have no real way to determine exactly the available power of a whole wind farm under down-regulation. Therefore, PossPOW project aimed to develop a verified, industrially applicable and internationally accepted way to determine the possible power of a down-regulated offshore wind farm. Along the way, it was intended to improve the use of wake models for real-time cases to obtain real-time wind farm power curves which can then be fed into a dynamic control system.

To correct the reduced wake effect during down-regulation is the conceptual basis of the PossPOW algorithm, see Figure. In order to do that, first we have introduced a local effective wind speed estimation procedure based on the turbine SCADA data [15].

The next stage is to feed the effective wind speeds at the upstream turbines to a wake model to estimate the velocity deficit for normal operation and replace the down-regulated wake. The wake models are benchmarked using an onshore and an offshore wind farms and their targets of application are briefly described throughout the literature (e.g. [16]). The wake models capable of resolving high fidelity data are computationally costly to perform real-time or to be implemented online. On the other hand, the robust models are tuned and validated using 10-min averaged conventional data to achieve long-term statistics rather than to investigate dynamics inside the wind farm. Therefore, as one of the most advanced readily-available engineering models, the Larsen model is re-calibrated for real-time. To further enhance the wake modelling, the local turbulence intensity using the effective wind speed [17] is included in the calculations.

The test and validation of the algorithm is rather challenging since there is no actual measure of the available power on the wind farm scale. However, we can benefit from the similarity in power production between the neighbouring rows in a simple layout like the Horns Rev-I wind farm. A series of dedicated experiments are conducted, in which two of the upstream turbines in Horns Rev-I offshore wind farm are curtailed under specific inflow conditions. Here in this study, the results of these down-regulation experiments for the estimation of the reserves in real-time, 30-sec provision and 15-min averaged error corresponding to most of the grid codes are presented.

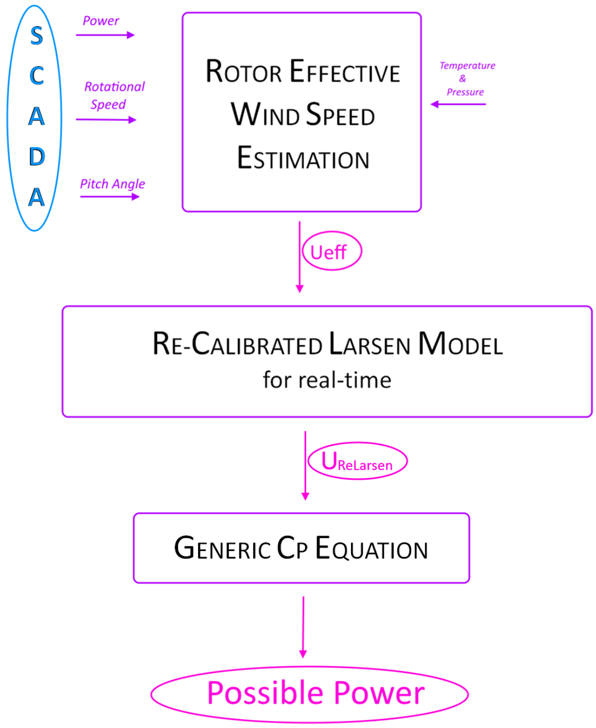

Fig. 1. PossPOW inputs and workflow

II. RESULTS & DISCUSSION

As mentioned earlier, the validation of the PossPOW algorithm under down-regulated operation was performed using experiments in Horns Rev-I where the algorithm is compared to the current industry practice and shown to perform significantly better. Figure 2 shows that the median of the SCADA possible power signal error is approximately 35% where the distribution is also broad indicating higher uncertainty. On the other hand, the PossPOW algorithm seem to reduce that error remarkably down to 10% with a considerably narrower distribution.

To quantify the uncertainty in the real-time available power estimated by PossPOW, the first approach is to investigate the quantification and propagation of the input uncertainties as well as the parameter uncertainties in the algorithm, which is a complex and computationally intensive process for realistic engineering simulations. A variety of methodologies are available in literature, from basic convolution techniques [18] to commonly used Monte Carlo simulations [19], to more sophisticated stochastic spectral Galerkin approaches [20], [21], [22]. The implementation of the most suitable method(s) for the propagation will yield the "traditional" uncertainty quantification of the real-time available power estimated by the PossPOW. The other approach, which is implemented in this study, is based on the comparison between measurements and model outputs where the width of the modelling error distribution signifies

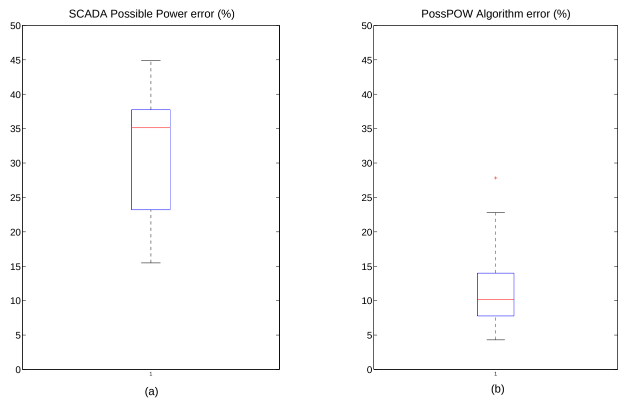

Fig. 2. Median (red line), 25th and 75th percentiles (edges of the box) of the percentage error of (a) the SCADA Possible Power and, (b) the PossPOW algorithm

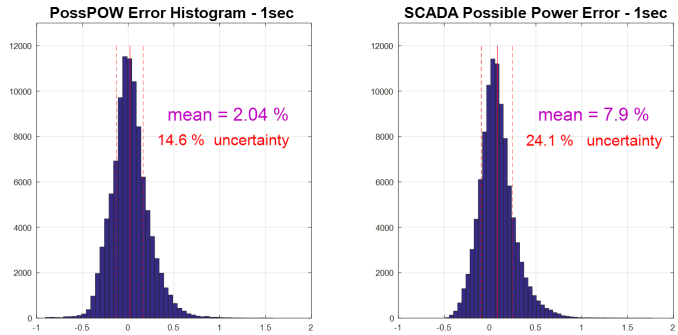

Fig. 3. The percentage error distribution of the estimated reserve power using PossPOW algorithm (left) and individual turbine available power SCADA signals (right). 8-hours data in total, 6 down-regulation experiments performed in Horns Rev-I

the model uncertainty and the mean indicates the model bias. This kind uncertainty assessment is purely based on data analysis, thus claimed to be objective. The error is defined as the normalized difference between estimated possible power of the turbine behind the curtailed turbine (under the down-regulated wake) and its neighbour that is defined as the reference turbine. The error histogram of the real-time (1-sec) calculations for both the PossPOW and the current practice of aggregated SCADA signals are given in Figure 3. The mean error of almost 8% of the SCADA Possible power indicates the inaccuracy of the operations monitoring using only the turbine data for off-performance conditions. Note that the uncertainty in this study, including Figure 3, is defined as the half of the size of the 16th and 84th percentiles (half of the 68% confidence intervals) which are indicated in dashed lines.

The 30-sec provision of the reserve power estimation might be found useful considering the technical difficulties to adjust the market to real-time application. For that reason, the results are updated for 30-sec averaged available power estimations where a considerable improvement in the bias and uncertainty for both of the approaches are expected. However, lack of information occurred due to averaging with 960 data points in total to analyse. In order to improve the statistics, the bootstrap method is implemented to the time

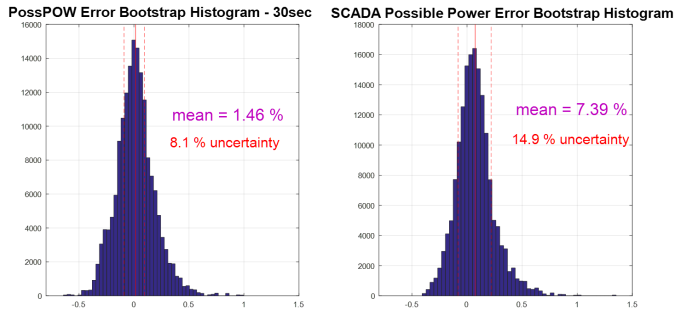

Fig. 4. The percentage error distribution for 30-sec provision of the estimated reserve power using PossPOW algorithm (left) and individual turbine available power SCADA signals (right). Circular bootstrapping is applied [23].

series following a circular block re-sampling procedure [23], in a similar fashion to Nygaard et al. [24], to systematically quantify the uncertainty in real-time available power. The results in Figure 4 show that the main improvement in the 30-sec provision of the reserve power compared to the real-time is in the width of the error distribution rather than the mean. Both Figure 3 and 4 indicate the importance of including the real-time flow modelling in the available power estimations as a clear improvement is observed, both in terms of the inaccuracy and the risk embedded in the amount of reserves.

III. Conclusion & Future Work

The PossPOW algorithm converts the incident wind on the rotor to a free stream wind speed for the upwind turbine, advects it with newly developed real-time wake models to the next turbine, and calculates the power of this turbine under normal conditions, taking the local turbulence intensity into account. A preliminary data-based uncertainty quantification of this algorithm, which is the only verified real-time wind farm scale available power estimation today is presented. The previously performed down-regulation experiments in Horns Rev-I have been found promising in terms of higher accuracy and lower uncertainty compared to the good industry practice of estimating the wind farm scale available power. The data-based uncertainty assessment is to be compared with the traditional uncertainty quantification methods, where the input and parameter uncertainty is to be propagated within the model structure.

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